Year 4 — Differential Manifolds

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These notes are not endorsed by the lecturers, and I have modified them (often significantly) after lectures. They are nowhere near accurate representations of what was actually lectured, and in particular, all errors are almost surely mine (especially the typos!).

Contents

1 Manifolds

Reading: Hitchin Chapter 2
Manifolds are just geometric spaces that hold other geometric structures.

1.1 Topological Manifolds

Definition 1.1 (Topological Manifold)**.** A Topological space X, is a **topological manifold** of **dimension**, $n \in \mathbb{N}$ if,

1. X is **Hausdorff**,
2. X is **second countable**,
3. For all $x \in X$, there is an open neighbourhood $V \subseteq X$, and an open set $U \in \mathbb{R}^n$ and a homeomorphism, $\phi : U \to V$. That is, X is **locally homeomorphic** to $\mathbb{R}^n$.

Hausdorff and Second Countable are global topological conditions.

Definition 1.2 (Hausdorff)**.** X is Hausdorff if for all $x, y \in X$ where $x \neq y$, there is some open $U, V \subseteq X$ such that $x \in U$ and $y \in V$ then $U \cap V = \varnothing$.

Further,

Definition 1.3 (Second Countable)**.** X is second countable, if there exists a countable set $U_1, U_2, \dots$ open sets in X such that every open set in X is the union of some of the U_i's.

What does this mean? Well, X being second countable means X is not 'too big'. For instance, we need X second countable to show that 'every manifold is a submanifold of $\mathbb{R}^n$ for n sufficiently large' (Whitney Embedding Theorem). Some authors assume X is **paracompact** instead.

We now show $\mathbb{R}^n$ is second countable. Take the U_i's to be all the $B_r(x_1, \dots, x_n)$ for $x_1, \dots, x_n > 0$, rational. Hence as $\mathbb{Q}$ is dense, then every real is in a ball, but also $\mathbb{Q}$ is countable, we get the second countable result. If it is compact, then it is second countable.

The only sensible notion of 'morhpisms' of topological manifolds are continuous maps. Here are some examples / non-examples,

Example.

- $\mathbb{R}^n$ and S^n with the induced topology are topological manifolds of dimension n.
- (Non-example) The line with two origins, $\mathbb{R} \cup \mathbb{R}$ glued on $\mathbb{R} \backslash \{0\}$. This has two open subsets homeomorphic to $\mathbb{R}$. This satisfies condition (2-3), but not (1) as it isn't countable. Limits in this set isn't unique.
- Let S be any set, make S into a topological set with the discrete topology. Then S is a topological manifold of dimension 0, if and only if S is countable (needed for S to be a Second Countable). As we need these TS's to be second countable, we need countably many connected components.

1.2 Smooth Manifolds

In some sense, a manifold is general place where you can do calculus. We are trying to avoid using coordinates (this is the interesting bit for applied maths and geometry). On topological manifolds there is no meaningful notion of differentiable function. A **smooth structure** is an additional structure on a topological manifold which functions are differentiable. We express this in terms of an **atlas of charts**. There is an alternative way to do this via sheaves of smooth functions.

Definition 1.4 (Chart)**.** Let X be a topological space. A **chart** of X, of dimension $n \in \mathbb{N}$, is a pair (U, ϕ) with $U \subseteq \mathbb{R}$ open and $\phi : U \to V$ is a continuous map, such that $\phi(U) \subseteq X$ is open, and $\phi : U \to \phi(U)$ is a homeomorphism.

That is relatively boring. This tells us that X is locally homeomorphic to $\mathbb{R}^n$. Here is a more interesting definition,

Definition 1.5 (Compatible)**.** Two charts (U, ϕ) and (V, ψ) are compatible if $\psi^{-1} \circ \phi : \phi(\psi(v)) \to \psi^{-1}(\phi(v))$ is a smooth map between open subsets of $\mathbb{R}^n$.

Definition 1.6 (Smooth)**.** All partial derivatives exist. We call them C^∞.

It is automatic that $\psi^{-1} \circ \phi$ is a **homeomorphism** between open subsets of $\mathbb{R}^n$. We want smooth aswell.

$$\begin{tikzcd}
\phi^{-1}(\psi(v)) \subseteq U \subseteq \mathbb{R}^n \arrow[dr, "\phi"] \arrow[dd, "\psi^{-1}\circ\phi"'] & \\
& X \arrow[dl, dashed, shift left, "\psi^{-1}"] \\
\phi^{-1}(\psi(v)) \subseteq U \subseteq \mathbb{R}^n \arrow[ur, "\psi"] &
\end{tikzcd}$$

Definition 1.7 (Atlas)**.** An **atlas** on X of dimension $n \in \mathbb{N}$ is a family $\{(U_i, \phi_i) : i \in \mathcal{I}\}$ is a family of charts of dimension n on X, such that,

1. (U_i, ϕ_i) and (U_j, ϕ_j) are compatable for all $i, j \in \mathcal{I}$
2. $X = \bigcup_{i \in \mathcal{I}} \phi_i(U_i)$

Definition 1.8 (Maximal Atlas)**.** An atlas is called **maximal** if it is not a proper subset of any other atlas.

If $\{(U_i, \phi_i) : i \in \mathcal{I}\}$ is an atlas on X, then the set of all charts (U, ϕ) on X that satisfy, they are compatible with (U_i, ϕ_i) for $i \in I$ is called a maximal atlas and is the unique maximal atlas containing the initial atlas.

Now for the punchline, the defintion of a smooth manifold

Definition 1.9 (Smooth Manifold)**.** A (smooth) manifold, (X, A) of dimension $n \in \mathbb{N}$, is a Hausdorff, second countable topological space X together with a maximal atlas A of dimension n. Then X is a topological manifold. Usually we just call X the manifold, leaving A implicit. [1]

A **chart** on X is an element of (U, ϕ) of A. Then $V = \phi(U)$ is open in X and $\phi^{-1} = (x_1, \ldots, x_n) : V \to \mathbb{R}^n$ is a **local coordinate system** on X.

Remark. We can use basically the same definition to define,

- C^k manifolds, modelled on $\mathbb{R}^n$ but the maps have k continuous derivatives. (C^0 manifolds are topological manifolds)
- Complex Manifolds, we just use $\mathbb{C}^n$ and holomorphic maps
- Banach Manifolds, we model of Banach spaces.

Example.

- The easiest example is $X = \mathbb{R}^n$, this has an atlas consisting of one chart $\{(\mathbb{R}^n, \mathrm{id})\}$, which isn't maximal but extends to a unique maximal atlas making $\mathbb{R}^n$ into an n-manifold.
- Let $X = S^n$. It has an atlas $\{(U_1, \phi_1), (U_2, \phi_2)\}$ where $U_1 = U_2 = \mathbb{R}^n$ and $\phi_1(U_1)$ is S^n minus the north pole and $\phi_2(U_2)$ is S^n minus the north pole.

[1] We are embarrassed about A as it is a really ugly piece of kit. Hence we leave it implicitly.

Another example of a manifold with an atlas,

Example. $X = T^n = \mathbb{R}^n \backslash \mathbb{Z}^n$ is an n-manifold, with an atlas $\{(U_\mathbf{y}, \phi_\mathbf{y}) : \mathbf{y} \in Y\}$ where $Y = \{\mathbf{y} = (y_1, \dots, y_n) : y_i \in \{0, \frac{1}{2}\}\}$. Then $U_\mathbf{y} = (-1/3, 1/3)^n \subseteq \mathbb{R}^n$ for all $\mathbf{y}$ and $\phi_\mathbf{y} : (x_1, \dots, x_n) \mapsto (x_1 + y_1 + \mathbb{Z}, \dots, x_n + y_n + \mathbb{Z})$. The transition maps are,

$$\phi_{\mathbf{y}_2}^{-1} \circ \phi_{\mathbf{y}_1} = x_i \mapsto \begin{cases} x_i + 1/2 \\ x_i \\ x_i - 1/2 \end{cases}$$

locally smooth map with a smooth inverse.

1.3 Smooth maps between manifolds

Definition 1.10. Let (X, A) and (Y, B) be manifolds of dimension m, n respectively and $f : X \to Y$ be a continuous map. We say that f is smooth if whenever $(U, \phi) \in A$ and $(V, \psi) \in B$ then $\psi^{-1} \circ f \circ \phi : (f \circ \phi)^{-1}(\psi(v)) \to V$ is a smooth map between open subsets of $\mathbb{R}^m$, $\mathbb{R}^n$.

$$\begin{tikzcd}
U \arrow[drr] & \supseteq & (f \circ \psi)^{-1}\psi(v) \arrow[r, "\psi^{-1} \circ f \circ \phi"] \arrow[d] & V \arrow[d, "\psi"] \\
 & & X \arrow[r] & Y
\end{tikzcd}$$

Remark.
- We note $\psi^{-1} \circ f \circ \phi$ is continuous, as f is continuous but we want it to be smooth.
- If $f = \mathrm{id}_X$, then this is the definition of compatibility of charts.
- You don't have to check this on all charts of X and Y. It is enough to check this for some subsets of charts convering X and Y, that is, for atlases not for maximal atlases.

Definition 1.11 (Diffeomorphism)**.** A **diffeomorphism** $f : X \to Y$ is a smooth map with smooth inverse. This is the natural notion of isomprohism of manifolds.

Lemma 1.12. If $f : X \to Y$ and $g : Y \to Z$ are smooth maps of manifolds, then $g \circ f : X \to Z$ is also a smooth map. Further, identities $id_X : X \to X$ are smooth. Therefore, manifolds and smooth maps form a category. [2]

Proof. To show $g \circ f$ is smooth, let (U, ϕ), (V, ψ) and (W, χ) be charts on X, Y and Z. Then we have,

$$\begin{tikzcd}
(f \circ \phi)^{-1}(\psi(v)) \cap (g \circ f \circ \phi)^{-1}(\chi(w)) \arrow[rr, "\chi^{-1} \circ (g \circ f) \circ \phi"] & (g \circ \psi)^{-1}(\chi(w)) \arrow[r, "\chi^{-1} \circ g \circ \psi"] \arrow[d, "\psi"] & W \arrow[d, "\chi"] \\
X \arrow[r, "f"'] & Y \arrow[r, "g"'] & Z
\end{tikzcd}$$

Then we have shown that, $\chi^{-1} \circ (g \circ f) \circ \phi$ is smooth on the open set $(f \circ \phi)^{-1}(\psi(v)) \cap (g \circ f \circ \phi)^{-1}(\chi(w))$. Of course[3] this is not what we want. We want $\chi^{-1} \circ (g \circ f) \circ \phi$ to be smooth on $(g \circ f \circ \phi)^{-1}(\chi(w))$. Luckily, Y is covered by $\phi(v)$ for charts (V, ψ). So $(g \circ f \circ \phi)^{-1})(\chi(W))$ is covered by subsets $(f \circ \phi)^{-1}(\psi(v)) \cap (g \circ f \circ \phi)^{-1}(\chi(w))$ over all charts (U, ψ) on Y. Therefore $\chi^{-1} \circ (g \circ f) \circ \phi$ is smooth on the whole set. So $g \circ f$ is smooth. The rest is easy [4] $\square$

[2] I got two lectures in before I met a category. RIP Applied Mathematician.
[3] this is not obvious
[4] I bet a tenner it isn't.

Another cool fact is, manifolds and smooth maps behave nicely under **products**. If X and Y are smooth manifolds of dimensions m and n, then there is a unique manifold structure on $X \times Y$ with dimension $m+n$, such that if (U, ϕ) and (V, ψ) are charts of X and Y. Then $(U \times V, \phi \times \psi)$ is a chart of $X \times Y$.

If $f : X \to Y$, $g : Y \to Z$ are smooth manifolds, then the direct product $(f, g) : X \to Y \times Z$ defined by $(f, g) : x \mapsto (f(x), g(x))$ is smooth. Further, if $f : W \to Y$ and $g : X \to Z$ are smooth, then the **product** $f \times g : W \times X \to Y \times Z$, defined by $(f \times g)(w, x) = (f(w), g(x))$ is also smooth.

2 Tangent Bundles and Cotangent Bundles

2.1 The Algebra $C^\infty(X)$ of a manifold X

Definition 2.1. Let X be a manifold. We write $C^\infty(X)$ for the set of smooth functions $f : X \to \mathbb{R}$. Then f is an $\mathbb{R}$-algebra under pointwise addition, multiplication and scalar multiplication.

If $\dim X > 0$ then $C^\infty(X)$ is infinitely dimensional. We can recover X completely, up canonical diffeomorphism from the $\mathbb{R}$-algebra $C^\infty(X)$. The points $x \in X$ are in a one-to-one correspondance with the $\mathbb{R}$-algevra morphisms $C^\infty(X) \to \mathbb{R}$ defined by $x \mapsto (x_* : f \mapsto f(x))$. This determines, X as a set.

The topology on X is the weakest such that $f : X \to \mathbb{R}$ is continuous for all $f \in C^\infty(X)$. There is then a unique manifold structure on X such that $f : X \to \mathbb{R}$ is smooth for all $f \in C^\infty(X)$[5].

Let $g : X \to Y$ be a smooth map an $g^* : C^\infty(Y) \to C^\infty(X)$ be an $\mathbb{R}$-algebra morphism. Coversely, any $\mathbb{R}$-algebra morphism $\gamma : C^\infty(Y) \to C^\infty(X)$ is g^* for some unique smooth $g : X \to Y$.

Moral: The $\mathbb{R}$-algebra knows everything about the manifold X.

Example (Example 2.1)**.** Define $a : \mathbb{R} \to \mathbb{R}$ by,

$$a(t) = \begin{cases} e^{-1/t} & t > 0 \\ 0 & t \leq 0 \end{cases}$$

This function is smooth. Now we define $b : \mathbb{R} \to \mathbb{R}$ by,

$$b(t) = \frac{a(t)}{a(t) + a(1-t)}$$

This function is smooth with $b(t) = 0$ for $t \leq 0$ and $b(t) = 1$ for $t \geq 1$. Now let X be an n-manifold $x \in X$ and we choose a chart (U, ϕ) on X with $0 \in U \subseteq \mathbb{R}^n$ where $\phi(0) = x$. Now choose $\varepsilon > 0$ with $\overline{B_{\sqrt{2}\varepsilon}(0)} \subset U$. Now define $c : X \to \mathbb{R}$ by,

$$c(x) = \begin{cases} b(2 - \frac{x_1^2 + \cdots + x_n^2}{\varepsilon^2}) \text{ if} x' = \phi(x_1, \ldots, x_n) \in U & \\ 0 & \text{otherwise} \end{cases}$$

and $\phi_{\mathbf{y}} : (x_1, \ldots, x_n) \mapsto (x_1 + y_1 + \mathbb{Z}, \ldots, x_n + y_n + \mathbb{Z})$. WE can say that c is a globally smooth function on X. It it 1 near x and 0 away from x. Further, the d_i are smooth on all of x and $(d_1, \ldots, d_n)$ are local coordinates on X near x.

2.2 Tangent Vectors and Tangent Space

Let X be a manifold and $x \in X$. We define a vector space $T_x X$ called the **tangent space** to X at x. Elements $v \in T_x X$ are the **tangent vectors**. Heuristically they point in some direction. we think of them as some velocity of a point moving in X.

Definition 2.2 (Tangent Vector)**.** Let X be a manifold and $x \in X$. A **tangent vector** at x is a linear map $v : C^\infty(X) \to \mathbb{R}$ satisfying some Leibnitz rule, $v(ab) = a(x)v(b) + b(x)v(a)$ for all $a, b \in C^\infty(X)$.

We notice that this is a linear map and to we have a vector space of tangent vectors. This is a vector subspace of $C^\infty(X)^*$ (the vector space dual).

[5] This is a lie, there is apparently not a unique manifold structure

Proposition 2.3. Let X be an n-manifold (U, ϕ) be a chart on X, and $(u_1, \ldots, u_n) \in U$ with $\phi(u_1, \ldots, u_n) = x \in X$. Then $v : C^\infty(X) \to \mathbb{R}$ is a tangent vector if and only if it is od the form,

$$v(a) = \sum_{i=1}^{n} v_i \frac{\partial}{\partial x_i}(a \circ \phi)\Big|_{(u_1, \ldots u_n)}$$

for some unique $v_1, \ldots, v_n \in \mathbb{R}$. Hence $T_x X \cong \mathbb{R}$, where $(x_1, \ldots, x_n)$ are local coordinates of X near x.

Proof. For the 'if' part, take $v_1, \ldots, v_n \in \mathbb{R}$ and set, $v(a) = \sum_{i=1}^{n} v_i \frac{\partial}{\partial x_i}(a \circ \phi)\Big|_{(u_1, \ldots u_n)}$ for $a \in C^\infty(X)$. Then $v(ab) = a(x)b(v) + v(a)b(x)$ follows from product rule of differentiation, so v is a tangent vector. For the 'only if' part, we can define some smooth $d_1, \ldots, d_n : X \to \mathbb{R}$ with $d_i \circ \phi(x_1, \ldots, x_n) = x_i - u_i$ in an open neighbourhood of x in X. Let $v \in T_x X$, and set $v_i = v(d_i)$ for $i = 1, \ldots, n$. Using Taylor's Theorem, for $a \circ \phi : U \to \mathbb{R}$ at $(u_1, \ldots u_n)$ we can write,

$$a = a(x) \cdot 1 + \sum_{i=1}^{n} \frac{\partial}{\partial x_i}(a \circ \phi)\Big|_{(u_1, \ldots, u_n) \cdot d_i} + \sum_{i,j=1}^{n} F_{ij} \cdot d_i \cdot d_j + g,$$

where $F_{ij} : X \to \mathbb{R}$ and $g : X \to \mathbb{R}$ are smooth with $g = 0$ in an neighbourhood of X. We write $g = g \cdot (1 - c)$ where $c = 1$ at $x \in X$. So,

$$\begin{aligned} v(a) &= a(x)v(1) + \sum_{i=1}^{n} \frac{\partial}{\partial x_i}(a \circ \phi)\Big|_{(u_1, \ldots, u_n)} \cdot v_i + \sum_{i,j=1}^{n} v((F_{ij} d_i) d_j) + v(g(1 - c)) \\ &= \sum_{i=1}^{n} \frac{\partial}{\partial x_i}(a \circ \phi)\Big|_{(u_1, \ldots, u_n)} v_i \end{aligned}$$

□

Example. Let $g : (-\varepsilon, \varepsilon) \to X$ be smooth with $\gamma(0) = x$. Define $v : C^\infty(X) \to \mathbb{R}$ by $v(a) = \frac{d}{dt}(a \circ \gamma(t)) = 0$. Then using the product rule we see $v \in T_x X$. So the velocity of a moving point $\gamma(t) \in X$ is a tangent vector at $\gamma(0)$.

Definition 2.4 (Covariantly Functorial)**.** Let $f : X \to Y$ be a smooth map of manifolds and $x \in X$ with $f(x) = y$. Define $T_x f : T_x X \to T_x Y$ by $(T_x f)(a) : a \mapsto v(a \circ f)$, for $v \in T_x X$ and $a \in C^\infty(Y)$. This is well defined. If $g : Y \to Z$ is smooth with $g(y) = z$ then $T_x(g \circ f) = T_y g \circ T_x f : T_x X \to T_z Z$. So tangent spaces are covariantly functorial.

Remark. Let $X = Y = \mathbb{R}$, then the tangent spaces are also naturally indentified with $\mathbb{R}$ by the basis of ∂_x and ∂_y. Hence it can be proved that, $T_x f = \frac{df}{dx}$.

2.3 Cotangent Spaces and 1-forms

Definition 2.5. Let X be a manifold and $x \in X$. Then the **cotangent space** $T_x^* X$ to be the dual vector space $(T_x X)^*$.

Elements of $T_x^* X$ are called 1-forms. If $(x_1, \ldots, x_n)$ are local coordinates on X near x then $\frac{\partial}{\partial x_1}, \ldots, \frac{\partial}{\partial x_n}$ are a basis for $T_x X$. We write $dx_1, \ldots, dx_n$ for the dual basis for $T_x^* X$. If $f : X \to Y$ is smooth and $x \in X$ with $f(x) = y$, we write $T_x^* X : T_y^* Y \to T_x^* X$ for the linear map dual to $T_x f : T_x X \to T_X Y$. For $g : Y \to Z$ smooth with $g(y) = z$ we have $T_x^*(g \circ f) : T_x^* X \circ T_y^* g$, so cotangent spaces are **contravariantly functorial**.

Proposition 2.6. Let X be a manifold and $x \in X$. We write $I_x = \{a \in C^\infty : a(x) = 0\}$, an ideal in $C^\infty(X)$. We write I_x^2 for the vector subspace of $C^\infty(X)$ generated by ab for $a, b \in I_x$, also an ieal in $C^\infty(X)$. Then there is a canonical isomorphism $T_x^* X \cong C^\infty(X)/(\langle 1 \rangle_R \oplus I_x^2)$. If $(x_1, \ldots, x_n)$ are local coordinates of X near x, them $\langle 1 \rangle_R \oplus I_x^2$ is the kernel of some surjective linear map $C^\infty(X) \to \mathbb{R}$ mapping $a \mapsto \left(\frac{\partial a}{\partial x_1}\Big|_x, \ldots, \frac{\partial a}{\partial x_n}\Big|_x \right)$

Proof. By definition, $T_xX \subset C^\infty(X)^*$. Thus there is a natural isomorphism, $T_x^* \cong C^\infty(X)/W$ where $W \subset C^\infty(X)$ is the vector subspace of $a \in C^\infty(X)$ with $v(a) = 0$ for all $v \in T_xX$, and the dual pairing $T_x^*X \times T_x^*X \to \mathbb{R}$ maps $(a + W, b) \mapsto v(a)$. If $(x_1, \ldots, x_n)$ are local coordinates at x, then $\frac{\partial}{\partial x_1}, \ldots \frac{\partial}{\partial x_n}$ are a basis for T_xX. So W is the kernel of $C^\infty(X) \to \mathbb{R}^n$ mapping the basis for $a \mapsto \left(\frac{\partial a}{\partial x_1}\Big|_x, \ldots, \frac{\partial a}{\partial x_n}\Big|_x \right)$. Usig Taylors Theorem, we can also see that $W = \langle 1 \rangle_R \oplus I_x^2$. $\square$

Definition 2.7 (Derivative)**.** Let X be a manifold, $x \in X$ and $a \in C^\infty(X)$. Define $d_xa \in T_x^*X$ to be the linear map $T_xX \to \mathbb{R}$ mapping $v \mapsto v(a)$. Equivalent under the isomorpihsm defined above, d_xa is $a + (\langle 1 \rangle_R \oplus I_x^2)$. We call d_xa the **derivative** of a.

If $(x_1, \ldots, x_n)$ are local coordinates on X near x, and $dx_1, \ldots, dx_n$ are the corresponding basis for T_x^*X, then $d_xa = \frac{\partial a}{\partial x_1}\Big|_x dx_1 + \cdots + \frac{\partial a}{\partial x_n}\Big|_x dx_n$. But dx_a makes sense without choosing coordinates.

3 Vector Fields

Let X be a smooth manifold with tangent bundle TX. Then by definition, a **vector field** is a smooth section v of TX, $v \in \Gamma^\infty(TX)$. This gives a vector $v_x \in T_xX$ for each $x \in X$ which vary smoothly with $x \in X$.

Think of v as the velocity as the velocity of a fluid in motion on X. Let $X = S^2$, the surface of the earth and v as the velocity of the wind.

3.1 Vector field as derivations, the Lie Bracket.

Proposition 3.1. Let X be a manifold. Then there is a natural one-to-one correspondence between vector fields $v \in \Gamma^\infty(TX)$ and linear maps $\delta : C^\infty(X) \to C^\infty(X)$ satisfying $(*)$

$$\delta(ab) = a\delta(b) + \delta(a)b \,\forall\, a, b \in C^\infty(X) \tag{$*$}$$

such that,

$$v_x(a) = (\delta(a))(x) \text{ for all } x \in X$$

such maps δ are called derivations.

Proof. Recall that a vector $v_x \in TX$ is a linear map $v_x : C^\infty(X) \to \mathbb{R}$ satisfying,

$$v_x(ab) = a(x)v_x(b) + b(x)v_x(a) \,\forall\, a, b \in C^\infty(X) \tag{$**$}$$

If $\delta : C^\infty(X) \to C^\infty(X)$ is a derivation, then restricting $(*)$ to x gives,

$$\delta(ab)|_x = a(x)\delta(b)|_x + b(x)\delta(a)|_x$$

so,

$$v_x : C^\infty \to \mathbb{R}, \quad v_x(a) = \delta(a)|_x,$$

lies in T_xX. Hence $X \to TX$, $v : x \mapsto (x, v_x)$ is a map such that $\pi \circ v = \text{id}$. Working in coordinates we see v is a smooth map, so $v \in \Gamma^\infty(TX)$.

If $v \in \Gamma^\infty(TX)$ we define $\delta : C^\infty(X) \to C^\infty(X)$ by $\delta(a)(x) = v_x(a)$. Then working in coordinates we see that $\delta(a) : X \to \mathbb{R}$ is smooth and so, $\delta(a) \in C^\infty(X)$ and $(**)$ for each $x \in X$ implies $(*)$. $\square$

This correspondence buys us something. We can't compose vector fields, but we can compose derivations. Take $\delta, \varepsilon : C^\infty(X) \to C^\infty(X)$ to be derivations and let $a, b \in C^\infty(X)$. Then

$$\begin{aligned}(\delta \circ \varepsilon)(ab) &= \delta(\varepsilon(ab))\\ &= \delta(a\varepsilon(b) + b\varepsilon(a))\\ &= \delta(a)\varepsilon(b) + a(\delta \circ \varepsilon)(b) + \delta(b)\varepsilon(a) + b(\delta \circ \varepsilon)(a)\end{aligned}$$

This is not a derivation, but this isn't suprising as $(\delta \circ \varepsilon)$ is second order. Let's try the other order,

$$\begin{aligned}(\varepsilon \circ \delta)(ab) &= \varepsilon(\delta(ab))\\ &= \varepsilon(a\delta(b) + b\delta(a))\\ &= \varepsilon(a)\delta(b) + a(\varepsilon \circ \delta)(b) + \varepsilon(b)\delta(a) + b(\varepsilon \circ \delta)(a)\end{aligned}$$

and so we can subtract these and get, cancelation. This gives us,

$$\begin{aligned}[\delta, \varepsilon](ab) = (\delta \circ e)(ab) - (\varepsilon \circ \delta)(ab)\\ = a[\delta, \varepsilon]b + b[\delta, \varepsilon]a\end{aligned}$$

which is familiar (Disseration Y3). Thus the commutator, is a derivation. The commutator is,

$$[\delta, \varepsilon] = (\delta \circ \varepsilon) - (\varepsilon \circ \delta).$$

Definition 3.2 (Lie Bracket)**.** Let X be a manifold, and $v, w \in \Gamma^\infty(TX)$ be vector fields. Then v, w correspond to derivations $\delta, \varepsilon : C^\infty(X) \to C^\infty(X)$ by Prop 3.1. So $[\delta, \varepsilon]$ is also a derivation. We define the **Lie Bracket** $[v, w] \in \Gamma^\infty(X)$ to be the vector field corresponding to $[\delta, \varepsilon]$ under Prop. 3.1.

If $(x_1, \dots, x_n)$ are local coordinates on $U \subseteq X$ then we may write $v = v_1 \frac{\partial}{\partial x_1} + \cdots + v_n \frac{\partial}{\partial x_n}$ and $w = w_1 \frac{\partial}{\partial x_1} + \cdots + w_n \frac{\partial}{\partial x_n}$ for $v_i, w_j : U \to \mathbb{R}$ smooth. Then δ, ε act locally by $\delta \circ a = v_1 \frac{\partial a}{\partial x_1} + \cdots + v_n \frac{\partial a}{\partial x_n}$ and $\varepsilon = w_1 \frac{\partial a}{\partial x_1} + \cdots + w_n \frac{\partial a}{\partial x_n}$. So computing $\delta \circ \varepsilon(a) - \varepsilon \circ \delta(a)$ show, that

$$[v, w] = \sum_{i,j=1}^{n} \left(v_i \frac{\partial w_i}{\partial x_i} \right) \frac{\partial}{\partial x_j} - \left(w_j \frac{\partial v_i}{\partial x_j} \right) \frac{\partial}{\partial x_i}$$

in local coordinates. You may ask why we didn't write this expression until the end, but now we know that this is **COORDINATE INDEPENDENT!** That is, if we change coordinates the components change via Jacobian, but it cancels!

Note. We note that $[v, w] = -[w, v]$

Proposition 3.3. Let u, v, w be vector fields on X. Then the Lie brackets satisfy the Jacobi identity,

$$[u, [v, w]] + [v, [w, u]] + [w, [u, v]] = 0 \tag{$***$}$$

Proof. Let $\gamma, \delta, \varepsilon$ be the derivations corresponding to the vector fields u, v, w. Then $(***)$ corresponds to the equation,

$$\begin{aligned}[\gamma, [\delta, \varepsilon]] + [\delta, [\varepsilon, \gamma]] + [\varepsilon, [\gamma, \delta]] &= \gamma(\delta\varepsilon - \varepsilon\delta) - (\delta\varepsilon - \varepsilon\delta)\gamma + \delta(\varepsilon\gamma - \gamma\varepsilon) - (\varepsilon\gamma - \gamma\varepsilon)\delta + \varepsilon(\gamma\delta - \delta\gamma) - (\gamma\delta - \delta\gamma)\varepsilon \\ &= 0^6\end{aligned}$$

□

Definition 3.4 (Lie Algebra)**.** A Lie Algebra over some field $\mathbb{K}$ is a k-vectorspace V and bilinear map $[,] : V \times V \to V$ with $[u, v] = -[v, u]$ and the Jacobi identity[7].

3.2 Flowing along a vector field

Definition 3.5 (One-parameter group)**.** Let X be a manifold. Then a **one-parameter group of diffeomorphisms** of X is a smooth map $\phi : \mathbb{R} \times X \to X$ satisfying, writing that $\phi_t : X \to X$ defined by $\phi_t = \phi(t, x)$, then

- $\phi_t : X \to X$ is a diffeomorphism,
- $\phi_0 = \mathrm{id}_X$,
- $\phi_{s+t} = \phi_s \circ \phi_t$ for all $s, t \in \mathbb{R}$.

Then, $t \mapsto \phi_t$ is a group momorphism $R \to \mathrm{Diff}(X)$ (the group of diffeomorphisms).

Given such ϕ, define $\delta : C^\infty(X) \to C^\infty(X)$ by $\delta(a) = \frac{d}{dt}\big|_{t=0} (a \circ \phi_t)$. We have

$$\begin{aligned}\delta(ab) &= \frac{d}{dt}\bigg|_{t=0} ((a \circ \phi_t)(b \circ \phi_t)) \\ &= (a \circ \phi_t)|_{t=0} + \frac{d}{dt}\bigg|_{t=0} (b \circ \phi_t) + (b \circ \phi_t)|_{t=0} \frac{d}{dt}\bigg|_{t=0} (a \circ \phi_t) \\ &= a\delta(b) + b\delta(a) && \text{as } \phi_0 = \mathrm{id}\end{aligned}$$

Hence δ is a derivation, so it corresponds to $v \in \Gamma^\infty(TX)$ by Prop. 3.1. We have $v_x = \frac{d}{dt}\big|_{t=0} \phi_t(x)$. THen for each one-parameter family of diffeomorphisms ϕ on X gives a vector field V on X. We will show that under certain additional conditions (e.g. X is compact) each V corresponds to a ϕ. X and ϕ

[7]Now, this is the good stuff.

4 Tensor Products and Exterior Algebras

4.1 Tensor Products of vector spaces

Definition 4.1. Let V, W be finite dimensional vector spaces over $\mathbb{R}$. We define a vectorspace $V \otimes W$ called the **tensor product** of V, W with the properties,

- if $v \in V$ and $w \in W$ there is an element $v \otimes w \in V \otimes W$,
- This is billinear, that is $(\lambda v_1 + \mu v_2) \times w = \lambda(v_1 \otimes w) + \mu(v_2 \otimes w)$ and $v \otimes (\lambda w_1 + \mu w_2) = \lambda v \otimes w_1 + \mu v \otimes w_2$ for $v_1, v_2 \in V$, $w_1, w_2 \in W$ and $\lambda, \mu \in \mathbb{R}$
- $\dim(V \otimes W) = \dim V \cdot \dim W$. Futher, If $v_1, \dots v_n$ and $w_1, \dots, w_n$ are basis of V and W then $v_i \otimes w_j$ for $i = 1, \dots, n$ and $j = 1, \dots, n$ is a basis for $V \otimes W$.
- $V \otimes W$ has the universal property, that if $B : U \times W \to U$ is a billinear map to a vector space U, then there is a unique map $\beta : V \otimes W \to U$ with $B(v, w) = \beta(u \times w)$ for $v \in V$ and $w \in W$.

One way to efine $V \otimes W$ is as the dual vector space, $V \otimes W := B^*_{v,w}$, where $B_{v,w} = \{B : V \times W \to \mathbb{R} \text{ billinear map}\}$. If $v \in V$ or $w \in W$ then $v \otimes w : B_{v,w} \to \mathbb{R}$ is given by $(v \otimes w)(B) = B(v, w)$. Then the $(i) - (iv)$ are easy to check. Tensor products can also be defined for infinite dimensional vector spaces, which satisfy (i), (ii) and (iv), but this definition doesn't work as $(V^*)^* \ncong V$ in infinite dimensions.

We know some more things! The tensor product is associative, $U \otimes (V \otimes W) \cong (U \otimes V) \otimes W$ (this is a natural isomorphism), it's commutative $U \otimes W \cong W \otimes U$, and the distribute over $\oplus$,

$$U \otimes (V \oplus W) = (U \otimes V) \oplus (U \mathrm{op} W).$$

4.2 Tensor Algebras and exterior algebras

Definition 4.2 (Tensor Algebra)**.** Let V be a finite-dimensional $\mathbb{R}$-vector space. Then we can form, $V, V \otimes V, V \otimes V \otimes V, \dots$ and $\otimes^k V = V \otimes V \otimes \dots \otimes V$. By convension $\otimes^0 V = \mathbb{R}$. Then the **tensor algebra** is $T(V) = \bigotimes_{k=0}^{\infty} \otimes^k V$

It is an associative algebra with a product, $\otimes$ given by $(v_1 \otimes \dots \otimes v_k) \otimes (w_1 \otimes \dots \otimes w_\ell) = v_1 \otimes \dots \otimes v_k \otimes w_1 \otimes \dots \otimes w_\ell \in \otimes^{k+\ell} V$. It has identity $1 \in \mathbb{R} = \otimes^0 V$. The symmetric group, S_k, of permutations of $1, 2, \dots, k$ acts on $\otimes^k V$ by permuting the k factors, so that $\sigma \in S_k$ acts by,

$$\rho_k : \otimes^k V \to \otimes^k V, \qquad \rho_k(v_1 \otimes \dots \otimes v_k) = v_{\sigma(1)} \otimes \dots \otimes v_{\sigma(k)}$$

where $\rho_k : S_k \to \mathrm{Aut}(\otimes^k V)$ the representation.
We define $\Lambda^k V$ to be the vector subspace of $\otimes^k V$ on which S_k acts antisymmetrically that is,

$$\Lambda^k V = \{\alpha \in \otimes^k V : \rho_k(\sigma)\alpha = \mathrm{sgn}(\sigma)\alpha\}$$

where $\mathrm{sgn} : S_k \to \{\pm 1\}$ is the usual group morphism. There is a projection $\pi : \otimes^k V \to \Lambda^K V$ by $\pi : \alpha \mapsto \frac{1}{k!} \sum_{\sigma \in S_k} \mathrm{sgn}(\sigma) \rho_k(\sigma)\alpha$. It is surjective with $\pi \circ \pi = \pi$ and we can also consider $\Lambda^k V$ as the quotient space $\Lambda^k V = \otimes^k V / \operatorname{Ker} \pi$, rather than a subspace $\Lambda^k V \subseteq \otimes^k V$.

The 'exterior product', $\wedge : \Lambda^k V \times \Lambda^\ell V \to \Lambda^{k+l} V$ is the composition,

$$\Lambda^k V \times \Lambda^\ell V \xhookrightarrow{\text{inc}} \otimes^k V \times \otimes^\ell V \xrightarrow[\Lambda]{\otimes} \otimes^{k+\ell} V \xrightarrow{\pi} \Lambda^{k+\ell} V$$

It is associative as $\otimes$ is associative. We have $\Lambda^- V = \otimes^0 V = \mathbb{R}$, $\Lambda^1 V = V$ and $\Lambda^k V$ has dimension $\binom{n}{k}$, $n = \dim V$. If we have $v_1, \dots, v_n$ is a basis for V, then

$$\{v_{i1} \wedge v_{i2} \wedge \dots \wedge v_{ik} : 1 \le i_1 < i_2 < \dots < i_k \le n\}.$$

In particulat $\Lambda^n V \subseteq \mathbb{R}$ and $\Lambda^k V = 0$ for $k > n = \dim V$.

The **exterior algebra** is,

$$\Lambda^* V = \bigoplus_{k=0}^{n=\dim V} \Lambda^k V.$$

It is also an associate algebra under the $\wedge$. It has identity $1 \in \mathbb{R} = \Lambda^0 V$. It has dimension,

$$\sum_{k=0}^{n} \binom{n}{k} = 2^n.$$

Tensor products and exterior products are functorial under linear maps of vector spaces. That is, if $\alpha : T \to V$, $\beta : U \to W$ are maps of vector spaces, and we get the linear maps,

$$\alpha \otimes \beta : T \otimes U \to V \otimes W,$$

defined by,

$$(\alpha \otimes \beta)(t \otimes u) = (\alpha(t)) \otimes (\beta(t)) \forall t \in T, u \in U.$$

If $\alpha : V \to W$ is linear. we get,

$$\otimes^k \alpha : \otimes^k V \to \otimes^k W$$

defined by $\omega^k \alpha : v_1 \otimes \ldots \otimes v_k \mapsto \alpha(v_1) \otimes \ldots \otimes \alpha(v_n)$ and,

$$\Lambda^k \alpha : \Lambda^k V \to \Lambda^k W.$$

defined by,

$$\Lambda^k \alpha : v_1 \wedge \cdots \wedge v_k \mapsto \alpha(v_1) \wedge \cdots \wedge \alpha(v_k).$$

We can think of $\mathbb{R}^m \otimes \mathbb{R}^n$ as $m \times n$ matrices.

Example. Let A be an $m \times n$ matrix, which is a linear map $A : \mathbb{R}^n \to \mathbb{R}^n$. Then $\Lambda^n \mathbb{R}^n \cong \mathbb{R}$ and therefore, $\Lambda^n A : \Lambda^n \mathbb{R}^n \to \Lambda^n \mathbb{R}^n$ which is just multiplication by a real number and this $\det A$. Prove this.

4.3 Algebraic Operations on vector bundles

Let X be a manifold, our operations $V^*, V \oplus W, V \otimes W, \otimes^k V, \Lambda^k V$ on vector spaces also make sense on vector bundles on X.

Proposition 4.3. Let $E \to X$ and $F \to X$ to be vector bundles on a manfold X. Then there are natural vector bundles correpsonding to,

$$E^*, E \oplus F, E \otimes F, \otimes^k E, \Lambda^k V,$$

whose fibers satisfy, $E^*|_x = (E|_x)^*$, $(E \oplus F)|_x = E|_x \oplus F|_x$, and so on.

Proof. Let's just talk about the tensor product. As a set we define $E \otimes F$ to be,

$$E \otimes F = \{(x, \alpha) : x \in X, a \in E_x \otimes F_x\}.$$

Our problem is to put a manifold on here so we get a vector bundle. The projection, $\pi : E \otimes F \to X$ maps $\pi : (x, \alpha) \mapsto x$. Then we show there is a canonical manifold structure on this set $E \otimes F$, making $E \otimes F \to X$ into a vector bundle, such that if $U \subseteq X$ is an open neighbourhood of $x \in X$ with local trivialisation,

$$\begin{array}{ccc} \pi'_E(U) & \cong & U \times \mathbb{R}^k \\ \downarrow & & \downarrow \\ U & = & U \end{array}$$

and similarly for F. Then we get,

$$\begin{array}{ccc} \pi'_{E\otimes F}(U) & \cong & U \times (\mathbb{R}^k \otimes \mathbb{R}^\ell) \\ \big\downarrow & & \big\downarrow \\ U & = & U \end{array}$$

$\square$

5 Integration

5.1 Manifolds with Boundary

The interval $[0, 1]$ and the unit disc are not manifolds, even topologically. They are not locally homoemorphic to $\mathbb{R}$, $\mathbb{R}^2$. But they are manifolds with boundary.

Definition 5.1 (Manifolds with Boundary)**. Manifolds with boundary** are defined as for manifolds, but using manximal atlases $\{(U_i, \phi_i) : i \in \mathcal{I}\}$ in which we allow $U \subseteq \mathbb{R}^n$ open or $U \subseteq [0, \infty) \times \mathbb{R}^{n-1}$ open.

To define compatible charts we need to define $f : U \to V$ is smooth for open $U, V \subseteq [0, \infty) \times \mathbb{R}^{n-1}$.
This means that all derivatives $\frac{\partial^k f}{\partial x_{i_1} \dots \partial x_{i_k}}$ exists and are contnuous on U including one-sided derivatives. It is a theorem that this holds if and only if f extends to smooth $\tilde{f} : \tilde{U} \to \tilde{V}$, $\tilde{U}$, $\tilde{V}$ open neighbourhoods of $U, V \in \mathbb{R}^n$.

Example.

- $[0, 1]$ is a manifold with boundary.
- $D^n = \{(x_1, \dots, x_n) \in \mathbb{R}^n : x_1^2 + \dots + x_n^2 \leq 1\}$ is a manifold with boundary,
- The square $[0, 1]^2$ is not a manifold with boundary, but it is one with corners.

Definition 5.2. Let X be a manifold with boundary, with dimension n, with maximal atlas $\{(U_i, \phi_i) : i \in \mathcal{I}\}$. The boundary of X is,

$$\partial X = \{x \in X : \exists (U_i, phi_i) \text{ on } X, U_i \subseteq [0, \infty) \times \mathbb{R}^{n-1}, \S = \phi_\infty(\prime, \S_\in, \dots \S_\backslash)$$

[8].

We define J to be the subset of $i \in \mathcal{I}$ with $U_i \subseteq [0, \infty) \times \mathbb{R}^{n-1}$ open. We set $V_j = \{y_1, \dots, y_{n-1} \in \mathbb{R}^{n-1} : (0, y_1, \dots, y_{n-1}) \in U_j\}$. Now we let $\psi_j : V_j \to \partial X$ where we see, $\psi_j(y_1, \dots, y_{n-1}) = \phi_j(0, y_1, \dots, y_{n-1})$. We see this is ψ_j defined a maximal atlas on ∂X, making it into an $(n-1)$-manifold without boundary.

If X is a manifold with boundary, with an orientation, we can define an orientation on ∂X. This requires an **orientation convention**. We convent that $(x_1, \dots, x_n) \in [0, \infty) \times \mathbb{R}^{n-1}$ are oriented local coordinates on X, then, $(x_2, \dots, x_n)$ are anti-oriented local coordinates on ∂X. Equivalently $d_1 \wedge \dots \wedge dx_n$ defines the orientation on X, then $-dx_2 \wedge \dots \wedge dx_n$ defines the orientation on ∂X.

Aside: The orientations is a map the base of $T_x X$, which is the determinant, so ± 1. Then this gives an idea for manifold of dimension 0.

Example. Lets take $[0, 1] = X$, with orientation $[dx]$. Then $\partial X = \{0\} \coprod \{1\}$, where 0 has the negative orientation and 1 has the positive orientation. This is consistent with,

$$\int_0^1 \frac{df}{dx} \mathrm{dx} = -\mathrm{f}(0) + \mathrm{f}(1)$$

for smooth $f : [0, 1] \in \mathbb{R}$. This is an example of stokes theorem.

Exterior forms $\alpha \in \Omega^k(X)$ on a manifold with boundary X can be restricted to the boundary $\alpha|_{\partial X} \in \Omega^k(\partial X)$. This can be regarded as a pullback, $\alpha|_{\partial X} = i^*(\alpha)$, $i : \partial X X$ the inclusion which is a smooth embedding.

[8] $x_1 = 0$ as we want to be on the boundary of $[0, \infty)$

5.2 Stokes Theorem

Theorem 5.3 (Stokes Theorem)**.** Let X be an oriented n-manifold with boundary, so that ∂X is an oriented $(n-1)$-manifold, and let $\alpha\Omega^{n-1}(X)$ with $\mathrm{supp}(\alpha)$ compact. Then,

$$\int_X \mathrm{d}\alpha = \int_{\partial \mathrm{X}} \alpha|_{\partial \mathrm{X}} \,.$$

Proof. Choose an atlas $\{(U_i, \phi_i) : i \in \mathcal{I}\}$ of oriented charts on X, and we take a subordinate partion of unity $\{\eta_i : i \in \mathcal{I}\}$. Then let $J \subseteq \mathcal{I}$ be the subsrt of $j \in \mathcal{I}$ with $U_j \subseteq [0, \infty) \times \mathbb{R}^{n-1}$ open, and set

$$V_j = \{(y_1, \dots, y_{n-1}) \in \mathbb{R}^{n-1} : (0, y_1, \dots, y_{n-1}) \in U_j\}.$$

Now we let $\psi_j : V_j \to \partial X$ defined by $\psi_j(y_1, \dots, y_{n-1}) = \phi_j(0, y_1, \dots, y_{n-1})$. Then $\{(V_j, \psi_j) : j \in J\}$ is an atlas of anti-oriented charts of ∂X and $\{\eta_j|_{\partial X} : j \in J\}$ is a subordinate partition of unity. Since $\mathrm{supp}\alpha$ is compact and $\{\eta_i : i \in \mathcal{I}\}$ is locally finite, $\mathrm{supp}\,\alpha \cap \mathrm{supp}\,\eta \neq \varnothing$ for only finitely many $i \in \mathcal{I}$. Thus $\alpha = \sum_{i\in\mathcal{I}} \eta_i \alpha$, with only finitely non-zero many terms. Hence,

$$\begin{aligned}\int_X \mathrm{d}\alpha &= \sum_{i\in\mathcal{I}} \int_X \mathrm{d}(\eta_\mathrm{i}\alpha)\\ &= \sum_{i\in\mathcal{I}} \int_{U_i} d(\phi_i^*(\eta_i\alpha))\end{aligned}$$

Now we fix $i \in \mathcal{I}$, then we write,

$$\phi^*(\eta_i\alpha) = \sum_{k=1}^{n} (-1)^{k-1} a_k \mathrm{dx_1} \wedge \cdots \wedge \mathrm{dx_{k-1}} \wedge \mathrm{dx_{k+1}} \wedge \cdots \wedge \mathrm{dx_n}.$$

where $a_k : U_i \to \mathbb{R}$ is smooth and compactly supported. Then,

$$\mathrm{d}(\phi^*(\eta_\mathrm{i}\alpha)) = \left(\sum_{\mathrm{k}=1}^{\mathrm{n}} \frac{\partial \mathrm{a_k}}{\partial \mathrm{x_k}}\right) \mathrm{dx_1} \wedge \cdots \wedge \mathrm{dx_n}.$$

So,

$$\int_{U_i} \mathrm{d}(\phi_\mathrm{i}^*(\eta_\mathrm{i}\alpha)) = \sum_{\mathrm{k}=1}^{\infty} \int_{\mathrm{U_i}} \frac{\partial \mathrm{a_k}}{\partial \mathrm{x_k}} \mathrm{dx_1} \wedge \cdots \wedge \mathrm{dx_n}.$$

If $i \in \mathcal{I} \setminus J$, so $U \sin \mathbb{R}^n$ open. Then,

$$\begin{aligned}\int_{U_i} \frac{\partial a_k}{\partial x_k} \mathrm{x_1} \wedge \cdots \wedge \mathrm{x_n} &= \int \cdots \int \left(\int \frac{\partial a_k}{\partial x_k}\right) \mathrm{dx_1} \dots \mathrm{dx_k} \dots \mathrm{dx_n}\\ &= 0\end{aligned}$$

If $i \in J$, then $k = 1$ is different, we get,

$$\begin{aligned}\int_{U_i} \frac{\partial a_1}{\partial x_1} \mathrm{dx_1} \dots \mathrm{dx_n} &= \int \cdots \int \left(\int \frac{\partial a_1}{\partial x_1} \mathrm{dx_1}\right) \mathrm{dx_2} \dots \mathrm{dx_n}\\ &= \int \cdots \int [a_1]_0^{x_1 \gg 0} \mathrm{dx_2} \dots \mathrm{dx_n}\\ &= \int \cdots \int -a_1(0, x_2, \dots, x_n) \mathrm{dx_2} \dots \mathrm{dx_n}\\ &= -\int_{V_i} a_1|_{x_1=0} \, \mathrm{dx_2} \dots \mathrm{dx_n}\\ &= \int_{V_i} \psi_i^*(\eta_i \; \alpha|_{\partial X}).\end{aligned}$$

Hence,

$$\begin{aligned}\int_X \mathrm{d}\alpha &= \int_{i\in\mathcal{I}}\int_X \mathrm{d}(\eta_i\alpha) \\ &= \sum_{j\in J}\int_{\partial X}\eta_j\ \alpha|_{\partial X} = \int_{\partial X}\alpha|_{\partial X}\,.\end{aligned}$$

□

Remark. Greens Theorem is a trivial consequence where $\alpha = P\mathrm{dx} + \mathrm{Qdy}$.